1971

Design and preliminary testing of a thermomechanical rock fragmentation apparatus

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DESIGN AND PRELIMINARY TESTING OF A

THERMOMECHANICAL ROCK FRAGMENTATION APPARATUS

By

GARY EARL FENTON, 1947-

A THESIS

Presented to the Faculty of the Graduate School of the

UNIVERSITY OF MISSOURI-ROLLA

In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

1971

Approved by

Terry J. Lehnhoff (Advisor) [illegible]

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ABSTRACT

The design characteristics of equipment to thermally weaken and mechanically fragment hard rock were developed and the apparatus constructed. An initial investigation of thermo-mechanical fragmentation was conducted on Missouri red granite.

The particles from the fragmentation tests were sized and this analysis was used in the Rittinger theory to calculate surface area breakage energy.

It was found that the application of thermal energy could reduce the surface area breakage energy per unit volume of material removed by as much as 41 percent. The use of kerfs in the rock increased the amount of material removed and permitted larger particles to be chipped off. The use of flame jets as the source of thermal energy increased the difficulty of collecting the particles for analysis because of the high exhaust velocity.

ACKNOWLEDGMENTS

The author wishes to extend his appreciation and sincere thanks for the personal encouragement and technical assistance of Dr. Terry F. Lehnhoff, his advisor. He is also grateful to his laboratory assistants, Ernie Goggin and Herbert Smith for their personal dedication. He sincerely appreciates the financial support for his work under the Department of Defense Contract DACA-45-69-C-0087 directed by Dr. George B. Clark of the Rock Mechanics and Explosives Research Center.

Finally, the author is indebted to his parents for support, encouragement, and patience during his educational process.

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E_1 = Jackhammer work output (ft-lb/min)

C = Constant

P = Mean effective pressure on Jackhammer piston ($lb/in.^2$)

A = Area of piston face ($in.^2$)

S = Length of stroke (in.)

W = Weight of piston and rifle nut (lb.)

E_2 = Surface area breakage energy (ft-lb)

d_o = Diameter of unbroken rock (in.)

d_i = Average diameters of screen fractions of rock particles (in.)

pct_i = Percent weight of diameter d_i

n = Number of screens

d_{cor} = Corrected diameter (in.)

d = Particle diameter from sieve analysis (in.)

c = $100/\delta$

δ = Thickness of particles in percent of observed diameters

S_w = Specific surface area - ratio of new surface area to old surface area

ρ = Density (g/cm^3)

TS = Table speed

NK = No kerf

KA = Kerf A (1.2 in. wide by .3 in. deep)

KB = Kerf B (1.6 in. wide by .2 in. deep)

B1 = Bit No. 1 - (1.5 in. diameter carset bit)

B2 = Bit No. 2 - (2.25 in. diameter carset bit)

B3 = Bit No. 3 - (1.75 in. diameter button bit)

B4 = Bit No. 4 - (2.0 in. diameter button bit)

NO = No offset between the jackhammer path and the heat source path

Off 1 = 1 in. offset

Off 2 = 2 in. offset

g = Acceleration of gravity (32.2 ft/sec^2)

k = Fraction of time of piston power stroke required for return stroke

L = Distance from nozzle to rock surface (in.)

"Is not my word like as a fire? saith the Lord; and like as a hammer that breaketh the rock in pieces?" *

*Jeremiah 23:29 King James Bible

I. INTRODUCTION

Methods of excavating soft and medium-hard rocks have advanced in the last decade both in performance and cost advantages much more than methods of excavating hard rock. Difficulty in penetrating hard rocks with mechanical cutters has been the primary factor delaying the advancement of hard rock excavation.

A research project to study the excavation of hard rock using combined mechanical and thermal methods of rock removal has been undertaken in the University of Missouri-Rolla Rock Mechanics and Explosives Research Center. Theoretical studies of the process of heat weakening and spallation include pertinent aspects of thermoelastic stresses, heat energy coupling efficiency, rock surface temperature, and temperature distribution as well as gradients. Theoretical studies of disintegration include surface chipping for particular indentors, kerf ridge removal, energy requirements and estimation of efficiency for heat assisted mechanical chipping. Types of rocks with dissimilar composition and spalling characteristics were selected for examination to substantiate the theoretical studies.

Excavation of hard rock by mechanical cutters alone is not economically feasible. The currently used drill-and-blast method of excavation is cyclic in nature and lacks the advantages of continuous operation and smooth boring ability. When heat sources are used to excavate hard rock by melting, very large quantities of energy are required and the process is economically unattractive on a large scale. When heat processes are employed to remove rock by spallation, the process is usually limited to types of rocks composed of a minimum of ten percent quartz. The combination of thermal weakening/spalling and mechanical disintegration appears to offer a promising potential for hard rock excavation because of the non-cyclic nature, economic feasibility (with some systems), and possible applicability to hard rocks not containing quartz.

With this in mind, an apparatus was designed and constructed for the purpose of performing thermomechanical disintegration tests on hard rocks. Because of its availability an FSJ-6 stone-shaping torch (flame jet) was selected as the initial heat source. A conventional pneumatic drill (jackhammer) was used for the mechanical chipping process. The apparatus was designed to pass the rock specimen first in front of the heat source and then in front of the pneumatic drill. The time lag between the heating and chipping processes as well as the heat input was controlled by the speed of the rock table. To simulate in situ conditions as nearly as possible large cubes approximately thirty inches on a side were used in the tests.

The design of the apparatus and the initial set of experiments performed to check the design and testing procedures are presented in this thesis.

II. REVIEW OF LITERATURE

The history and trial-and-error development of the pneumatic rock drill began about 100 years ago. Early drills were limited in the energy per blow they could transmit to rock by the performance of the bit. When a certain blow energy was exceeded, bit performance dropped off, thus it was necessary to be able to determine the blow energy of a pneumatic drill. Drop weight testing machines were employed for this purpose, but results would vary considerably depending on how the machine was utilized. In 1948, Ditson (1)* proposed a method of approximating the blow energy theoretically. Wells (2) discussed additional factors such as air pressure and size of drill and drill bit. The basic theoretical development of an equation for pneumatic drill work output was completed by Pfleider and Lacabanne (3). This equation was based on piston weight, cylinder area, length of stroke, and mean effective air pressure.

Within the last three decades flame jets have developed well enough for commercial use. Smith and Mitchell (4) described the use of a flame jet to produce a continuous spalling action in hard rock. Removal rates, exhaust velocities, and flame temperature along with practical applications of flame jets are discussed by Browning, et al. (5). They found that spalling rates may be optimized by matching the heat input rate to the characteristics of the minerals being tested. For granites and taconites, improved rock removal rates were obtained at flame temperatures much lower than those produced by the combustion of pure oxygen and fuel. Also it was found that maximum removal rates

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*Numbers in parentheses refer to the Bibliography.

from a flat surface were obtained (at a given flame temperature) for exhaust velocities as low as 1200 ft per sec.

The basic phenomenon of weakening a rock mass by the application of heat has been under study at the Massachusetts Institute of Technology since 1965 (Refs. 6-11). It was found that application of heat by a laser significantly reduced the strength of hard rock. Mechanical cutting directly after thermal weakening was investigated by Carstens, et al. (12). It was found in their tests that increases in rock removal rates directly attributable to the combination of heating with mechanical disintegration were limited to less than 50 percent.

The relation of rock properties to rapid excavation was given in a report by Clark, et al. (13), where it was found that such properties as conductivity, rock structure, and porosity affect the reaction of rocks to thermal treatment. Important thermal properties were found to be thermal expansion, changes due to temperature, diffusivity or conductivity, and heat capacity. Rock properties at elevated temperatures were given in reports by Marovelli and Veith (14) and Wingquist (15). Standard mechanical properties of the test material, Missouri red granite, were given in reports by Clark, et al. (16), and Rollins, et al. (17).

III. THEORY OF THERMOMECHANICAL FRAGMENTATION

Mechanically induced stresses are produced by impact of wedge or spherical indentors against a rock surface. When these stresses exceed a rock's tensile or shear strength, brittle fracturing or plastic yielding takes place. Beneath the area of impact there is usually a zone of finely crushed rock where fractures may be initiated. These fractures propagate to the rock surface breaking loose chips or fragments of rock.

Thermoelastic stresses are generated in a uniformly heated body when normal thermal expansion is prevented by external constraints. Non-uniform heating can also produce thermal stresses by the interaction of forces from different parts of the body that tend to expand at different rates.

The surface of a rock may be at the required spalling temperature while, according to Browning, et al. (5), the rock may be at its initial temperature at depths of only 1/8 inch below the surface. This sharp thermal gradient is a primary factor in causing the thermal stresses that result in fracture. The non-homogeneous composition of rocks is a factor that assists the formation of thermal stresses because the individual grains and crystals of the rock may have different coefficients of thermal expansion. A third factor in creating thermal stresses is phase changes in minerals. The importance of phase changes may be illustrated by quartz. Quartz crystals undergo a 0.82 percent volumetric expansion accompanying the alpha-to-beta phase transition at 573 deg C. Minerals surrounding the quartz crystals constrain the thermal expansion and thus produce high thermal stresses.

Rocks of all types permanently loose strength after being heated (13), especially if the rock is heated to temperatures above 600 deg C. Reasons for this permanent reduction in strength are chemical changes, spalling and/or cracks from anisotropic thermal expansion, and the formation of micro-cracks along grain boundaries. Micro-cracks form as the rock crystals and grains expand and contract due to heating and cooling. In this weakened condition a rock is more susceptible to mechanical chipping processes.

If the mechanical chipping process is applied to the rock while thermal stresses are still present, crack initiation and propagation is enhanced due to the superposition of thermal and mechanical stresses. If the heating process is followed directly by the mechanical chipping process the greatest advantage may be obtained. The direct combination of these two processes has been referred to as thermomechanical fragmentation.

IV. APPARATUS AND EQUIPMENT: DESIGN AND CHARACTERISTICS

A. MOUNTING APPARATUS

Rock test specimens that were 30 in. cubes weighing approximately one and one half tons made it necessary to design testing apparatus that would mechanically move the test block laterally across the line of action of the pneumatic hammer and flame jet. The framework was constructed of 6 by 2 channel iron, 2 by 2 angle iron, and 6 by 6 structural steel wide flange I-beams. The proposed thermal fracturing system (Figures 1, 2 and 3) required transverse, vertical, and lateral movement of the rock removal equipment relative to the rock. Final selection of the method of lateral movement of the rock, and vertical and transverse movement of the jackhammer and flame jet was decided upon for two reasons: 1) Secondary breakage of particles by the jackhammer would be prevented by allowing the particles to fall free from the vertical face of the rock. 2) The transverse thrust of the jackhammer against the rock would be controllable.

In addition to forces from the weight of the test specimen, there were inertial forces due to the reciprocating action of the jackhammer. The framework was made as rigid as possible by welding where possible and by bolting where members had to be removable. Lock nuts were used on all bolts to prevent loosening as a result of vibration. Because the structural geometry of the frame was analytically redundant and the loads were unknown, engineering judgement was used as the basis for obtaining structural integrity. After preliminary tests, the welds were checked and found to have small cracks. These joints were re-welded and later checks revealed no further cracks had developed. Possibilities of fatigue failures

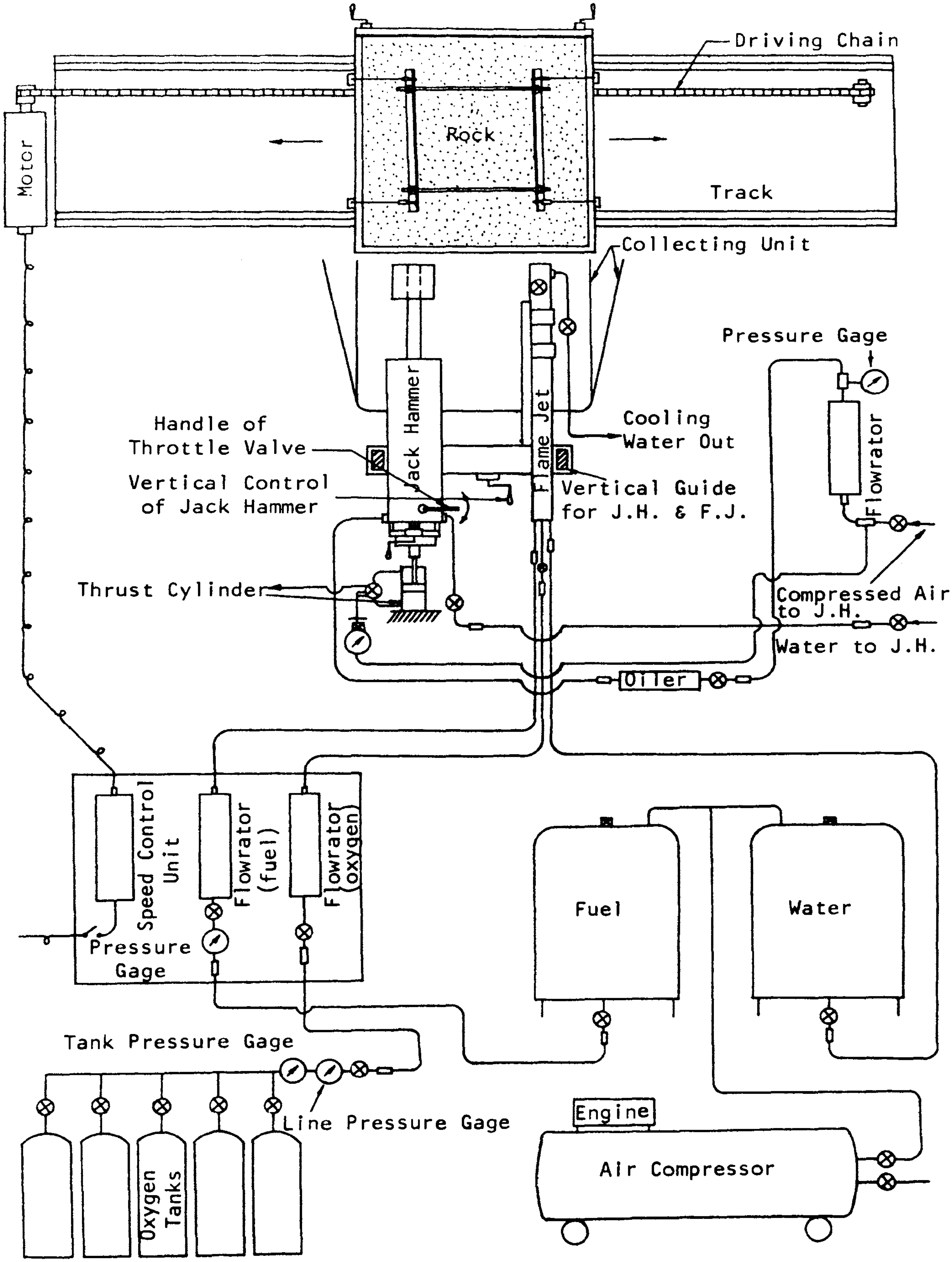

Figure 1. Schematic of Experimental Apparatus for Thermomechanical Fragmentation

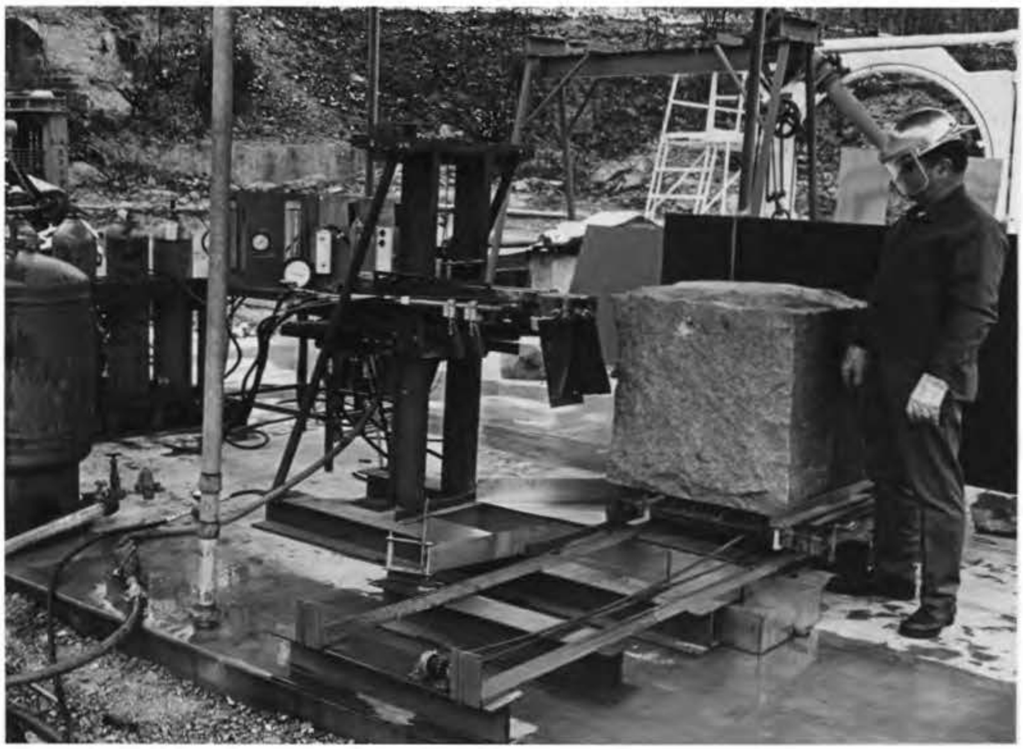

Figure 2. Pictorial View of Thermomechanical Fragmentation Apparatus

Figure 3. Front View of Thermomechanical Fragmentation Apparatus Showing Particle Collection Unit

may necessitate strengthening the joints by means other than re-welding in the future.

B. FLAME JET

An FSJ-6 stone-shaping torch, donated by Union Carbide, was used as the source of heat for thermal weakening/spalling. The torch was operated on oxygen and kerosene at pressures and flowrates suggested by the manufacturer (Table I) (Appendix A). Stoichiometric calculations gave the maximum combustion energy as 450,000 Btu/hr for the recommended operating conditions. Complete combustion produces a blue flame, but the flame jet had an orange-yellow flame signifying the presence of unburned carbon particles. Losses from incomplete combustion and other losses such as the energy the cooling water removes reduce the maximum combustion energy by a small but unknown amount. Energy available to the rock was reduced even more because of heat and kinetic energy losses of the high velocity exhaust gases. Losses due to vaporizing of the exiting cooling water were avoided by modifying the torch so that the water was not directed against the rock surface. The distance L (standoff) from the torch to the rock surface and the rate of traverse of the rock affect the coupling efficiency and the energy input into the rock. Estimates have indicated that the energy available to the rock was only 6 to 8 percent of the combustion energy (12). Other heat sources such as ion beam, electron beam, and infrared are considerably more efficient and will be utilized in future research.

The temperature of the flame was approximately 2400 deg C and the velocity of the exhaust gas was in the range of 4,000 to 10,000 ft/sec. (5). The combustion chamber is one inch inside diameter and the exhaust nozzle is a 3/16 inch DeLaval type.

TABLE I

Recommended Operating Conditions for FSJ-6 Flame Jet

	Ignition		Operation	
Consumable	Flow Rate	Pressure (lb/in^2)	Flow Rate	Pressure (lb/in^2)
Oxygen	100 (ft^3/hr)	150	500 (ft^3/hr)	135
Kerosene	15 (lb/hr)	120	22 (lb/hr)	120
Water	85 (gal/hr)	65	85 (gal/hr)	65

C. JACKHAMMER

The mechanical removal of rock particles was accomplished by a J50A jackhammer donated by the Ingersoll-Rand Company. Inlet operating pressure was maintained at approximately 90 lb/in.^{2} in order to maintain a 2-9/16 inch working stroke. The area of the piston face is 5.363 in.^{2} and the weight of the piston and rifle nut is 4.31 lbs.

The work output of the jackhammer was calculated by using the following equation developed (Appendix B) by Pflieder and Lacabanne (3):

$$E_1 = \frac{C\ P^{3/2}\ A^{3/2}\ S^{1/2}}{W^{1/2}} \tag{4-1}$$

where:

E_1 = Jackhammer work output (ft-lb/min)

C = Constant

P = Mean effective pressure (lb/in.^{2})

A = Area of piston face (in.^{2})

S = Length of working stroke (in.)

W = Weight of piston and rifle nut (lb.)

The mean effective pressure and the stroke were functions of the thrust and throttle setting, thus making it necessary to experimentally determine both quantities. The cylinder jacket on the jackhammer was tapped and a pressure transducer installed to monitor pressure. The stroke was to be determined from the incline of the rotation ratchet (30 linear inches of travel for one turn of the drill steel), and the rotations per minute and the cycles or blows per minute. However, when it was found that there was no direct connection between piston cycles and drill steel rotation (i.e the drill steel could "free wheel"), it was expedient to provide an inlet air pressure of 90 lb/in^2 and use the 2-9/16 inch working stroke determined by the manufacturer.

Throttle position number 4 and a thrust of 80 lbs were selected as optimum operating conditions (Table II) for the table speeds to be used. At higher thrust levels the jackhammer drilled a conventional hole and stalled because the rock was not moving fast enough. Operating the drill at position number 4 gave an acceptably smooth cut and removed more rock material than at any other throttle position.

D. THRUST CYLINDER

Initially it was planned to position the jackhammer relative to the rock and to clamp it during any given test. This proved unsatisfactory because the jackhammer could not move transversly with the contour of the rock face. A screw carriage was then employed on which to mount the jackhammer. This allowed the operator to move the jackhammer during the test to prevent stalling, but it also permitted the thrust to vary. The solution to this problem was the use of an air thrust cylinder, which permitted transverse movement of the jackhammer while maintaining constant thrust against the rock. Calibration of the air cylinder (Figure 4) in a Tinius Olsen testing machine revealed that a pressure of 13.2 lb/in^2 was necessary to produce the desired thrust of 80 lbs.

E. ROCK TABLE

The lateral movement of the rock, relative to the flame jet and jackhammer was accomplished by placing the test specimen on a table similar to a small flat car, which moved on inverted angle iron tracks. The movement of this table was calibrated (Figure 5) and operating speeds selected

TABLE II

Calibration Data for J50A Jackhammer

Throttle Setting	Calibration Thrust (lb)	Mean Effective Pressure (lb/in.^{2})	Line Pressure (lb/in.^{2})	Frequency (blows/sec)	Output Energy (joules/min)
1	26.0	11.5	102.0	16.9	19,320
	57.0	12.0	102.0	18.5	20,600
	92.0	11.5	101.0	18.9	19,320
2	26.0	22.0	97.0	26.0	51,130
	57.0	21.5	97.0	26.0	49,400
	92.0	22.0	97.0	25.0	51,130
3	26.0	27.0	95.0	29.0	69,420
	57.0	26.0	95.0	29.0	65,680
	92.0	26.0	95.0	29.0	65,680
4	26.0	31.0	90.0	30.0	85,520
	57.0	29.0	89.0	30.0	77,390
	92.0	27.0	89.0	29.0	69,520
5	26.0	30.0	85.0	31.0	81,410
	57.0	28.0	85.0	29.0	73,410
	92.0	27.0	85.0	29.0	69,520

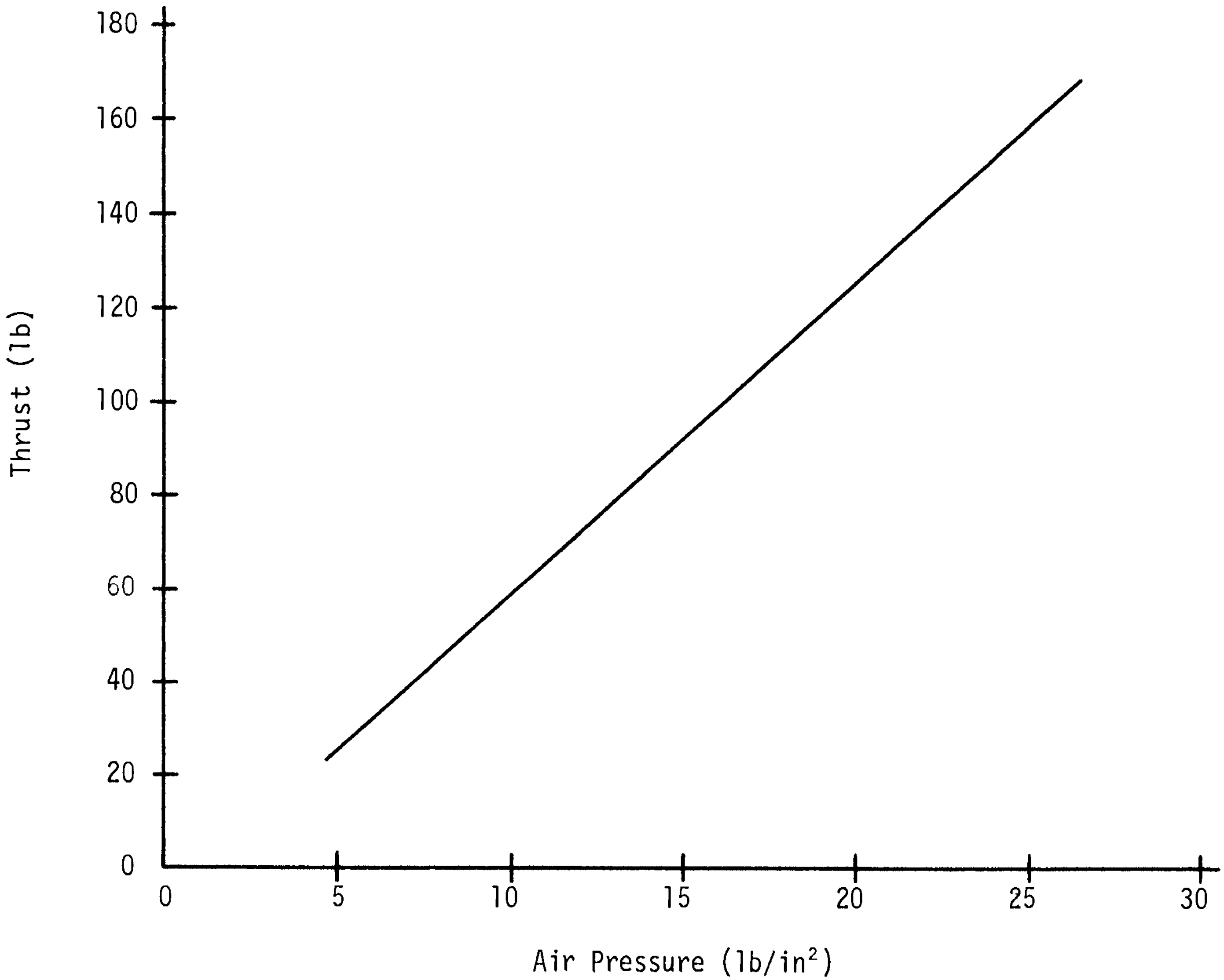

Figure 4. Calibration Curve for Thrust Cylinder

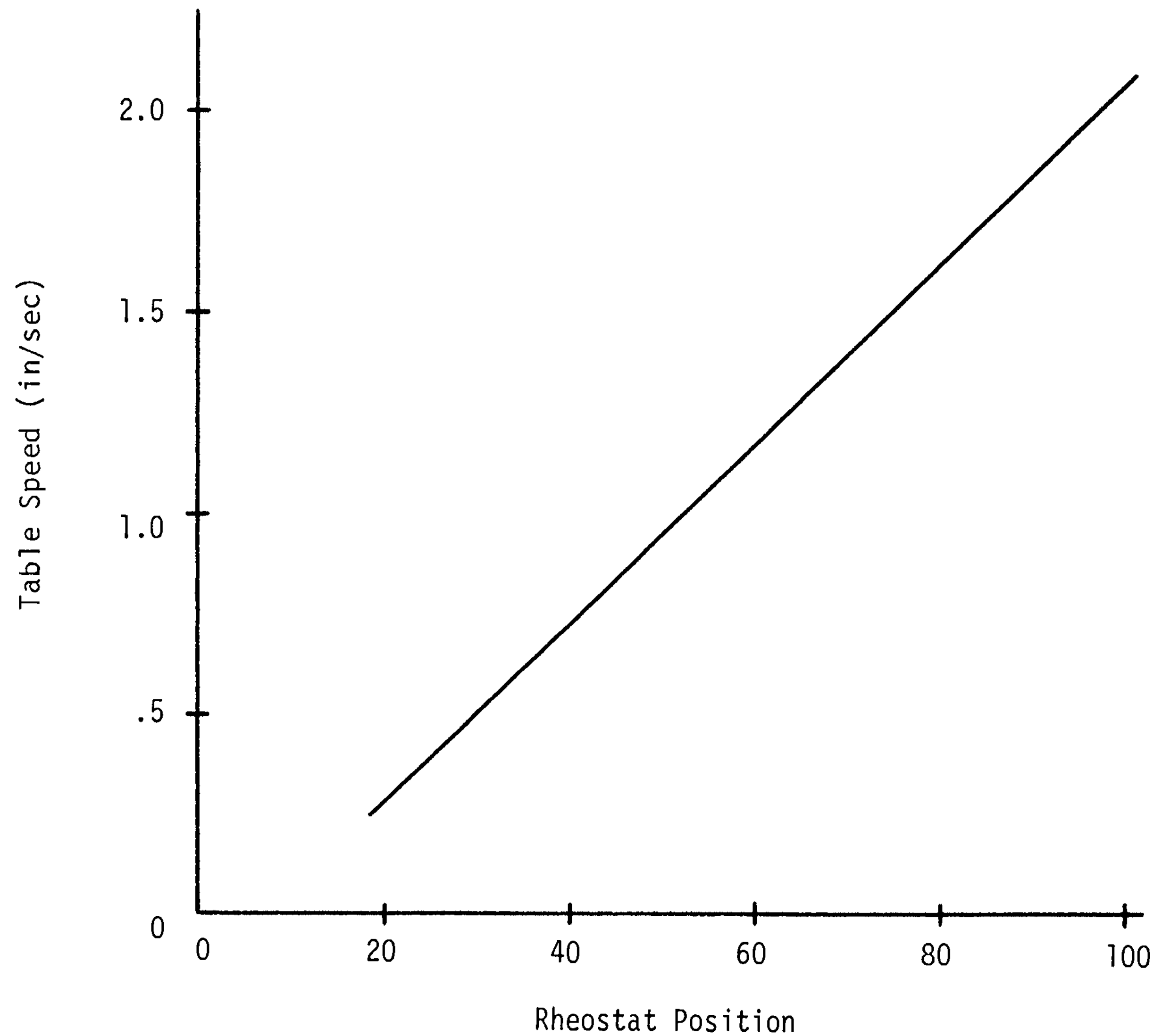

Figure 5. Calibration Curve for Rock Table Traverse Speed

as 0.51 in./sec, 0.96 in./sec, and 1.4 in./sec, corresponding to 30, 50, and 70 on the drive motor rheostat. At speeds less than 0.51 in./sec, the jackhammer would begin drilling a hole rather than traversing the face in a smooth uniform manner. At speeds greater than 1.4 in./sec inconsistent cutting occurred. The majority of tests were conducted at a table speed of 0.96 in./sec.

V. EXPERIMENTAL PROCEDURE

A. EXPERIMENTAL FACTORS

Important mechanical factors in the investigation of thermomechanical fragmentation were: 1) the amount of thermal energy that enters the rock, 2) the type of surface that the process was applied to, and 3) the positional relationship of the cutter to the heater. Other factors examined to investigate the test procedure itself were: 4) the type and size of bit used on the drill, and 5) the simultaneous versus independent operation of the heat source and cutter.

1. The flame jet is an inefficient method of transferring energy to a rock mass because energy is transferred by convection and rocks have low values of conductivity. The length of time the rock is exposed to the thermal treatment depends on the table speed. This and the distance of the nozzle from the face of the rock were the two controllable factors by which the amount of heat transfer could be varied. More thermal energy was transferred at slower table speeds and at closer standoff distances. Output energy (Table III) was based on theoretical calculations.

2. The type of surface affects both the amount of thermal energy transferred to the rock and also the force necessary to chip off rock particles. Tests with and without thermal treatment were conducted on flat surfaces and on two kerfs of different geometries. Kerf A was 1.2 in. wide and 0.3 in. deep, while Kerf B was 1.6 in. wide and 0.2 in. deep.

3. The lateral distance between the flame jet and jackhammer was fixed at 10 in. However, the vertical position or offset can be varied.

TABLE III

Theoretical Output Energy

	Output Energy (joules) Table Speed 30	Table Speed 50	Table Speed 70	Efficiency (percent)
Jackhammer*	75,800	40,350	27,580	60-70
Flame Jet**	10.51×10^6	5.59×10^6	3.82×10^6	6-8

*Based on 77,350 joules/min
**Based on 10.72×10^6 joules/min

Offsets of 2 in. and 1 in. were compared to on-line operation of flame jet and jackhammer.

4. Two styles of drill bits and two sizes of each style were investigated. Cross bits of 1-1/2 in. and 2-1/4 in. diameters were compared to button bits of 1-3/4 in. and 2 in. diameters. These tests were run without thermal treatment on a flat rock surface.

5. When thermal treatment was applied, simultaneous heating and cutting were employed on all but one test. The collection of all rock particles was important, consequently one test was run with independent heating and chipping. This was to determine if the high velocity exhaust of the flame jet was blowing away many particles.

B. MATERIAL PROPERTIES (Table IV)

Thirty-inch cubes of Missouri red granite were used for test specimens. One face was sawn flat in order to provide a smooth test surface. The sawn face was chipped off before any tests were conducted in order to have equivalent surface conditions on all tests.

C. TESTING PROCEDURE

The procedure outlined below was followed on all tests.

a. Set rheostat for desired table speed.

b. Select height position on rock to run test.

c. Set air pressure on thrust cylinder to 13.2 lb/in.^{2} to give 80 lb thrust.

d. If flame jet is to be used, ignite, and set controls at recommended operating conditions. Place ignitied flame jet in holder adjusted to desired distance from face of rock.

TABLE IV

Properties of Missouri Red Granite

Density	2.60 (g/cc)
Impact Hardness (scleroscope)	53
Relative Drillability	9
Compressive Strength	119 $g/cm^2/10^4$
Compression Wave Velocity	4.52 cm/sec x 10^5
Apparent Porosity	.4%
Composition	Percent by Volume
Quartz	32.5
Potash Feldspar	42.5
Plagioclase Feldspar	25
Hornblende	trace
Hypersthene	trace
Magnetite	trace
Tensile Strength	9.71 x 10^6 N/M^2
Modulus of Elasticity	5.72 x 10^9 N/M^2
Coefficient of Thermal Expansion	13 x 10^{-6} CM/CM°C

e. Turn on switch for lateral movement of rock table.

f. Start jackhammer and apply horizontal thrust against rock when leading edge of rock is in front of drill bit.

g. Make one pass across the width of the rock.

h. Stop rock table, shut off jackhammer and flame jet.

i. Use vacuum sweeper and collecting unit to collect particles chipped off during test.

j. Remove particles from sweeper water trap filter and dry in oven.

D. PARTICLE ANALYSIS PROCEDURE

The chipping test sample was weighed and the weights recorded (Table V). Then the sample was analyzed (sized)using Tyler standard screens and a sonic sifter. Twenty five screens were used in the analysis. Beginning with 1.050 in., the hole diameters decreased by $\sqrt{2}$ for the first 15 screens. The hole diameters in the remaining 9 screens (149 microns or .0059 in. opening and smaller) decreased by a factor of $\sqrt{2}/2$. Particles smaller than .0015 in. (37 microns) were caught in a fines collection pan and given an equivalent size of .0008 in. The total amount of material removed from one individual test varied from 185.3 grams to 1009.3 grams. For analysis purposes the test samples were divided to within the range of 25 to 100 grams. It was possible to divide the total chipping test sample by a factor of 2, 4, or 8 and still retain the same percentage of each size of particles. The surface breakage energy was evaluated by using Rittinger's (18-19), Kick's (20), and Bond's (21) theories. The material on each successive screen was divided by the total analysis sample and these numbers (expressed in percent) were used in the theories to compute the surface breakage energy.

TABLE V

EFFECTIVE CHIPPING ENERGY-PRELIMINARY TESTS

Description of Test	Material Removed (grams)	Total Surface Breakage Energy (joules)	Specific Surface Breakage Energy (joules/cc)	Total** Energy (joules)	Specific Energy (joules/cc)
TS30 B1 NK w/o heat	413.6	4554	28.63	49,270	309.7
TS50 B1 NK w/o heat	285.2	3220	29.37	26,227	239.1
TS70 B1 NK w/o heat	185.3	2286	32.08	17,927	251.5
TS30 B1 NK NO 10in.*	542.5	3522	16.89	364,570	1747.2
TS50 B1 NK NO 10in.	425.1	2944	18.02	193,927	1186.1
TS70 B1 NK NO 10in.	198.5	1686	22.07	132,527	1735.9
TS50 B1 NK w/o heat	285.2	3220	29.37	26,227	239.1
TS50 B1 KA w/o heat	491.8	5001	26.44	26,227	138.7
TS50 B1 KB w/o heat	429.1	4213	25.53	26,227	158.9
TS50 B1 NK NO 10in.	425.1	2944	18.02	193,927	1186.1
TS50 B1 KA NO 10in.	869.1	3008	8.99	193,927	580.2
TS50 B1 KB NO 10in.	673.0	3401	13.15	193.927	749.2
TS50 B1 NK w/o heat	285.2	3220	29.37	26,227	239.1
TS50 B2 NK w/o heat	237.1	2381	26.12	26,227	287.6
TS50 B3 NK w/o heat	239.4	2781	30.21	26,227	284.8
TS50 B4 NK w/o heat	365.4	3646	25.95	26,227	186.6
TS50 B1 NK w/o heat	285.2	3220	29.37	26,227	239.1
TS50 B1 NK NO 14in.	344.1	2403	18.16	193,927	1465.3
TS50 B1 NK NO 10in.	425.1	2944	18.02	193,927	1186.1
TS50 B1 NK NO 6in.	796.4	4846	15.83	193,927	633.1
TS50 B1 NK NO 10in.	425.1	2944	18.02	193,927	1186.1
TS50 B1 NK Off1 10in.	332.5	3368	26.34	193,927	1516.4
TS50 B1 NK Off2 10in.	344.6	2689	20.27	193,927	1463.2
TS50 B1 NK NO 10in.S	425.1	2944	18.02	193,927	1186.1
TS50 B1 NK NO 10in.I	1009.3	5307	13.68	193,927	499.6

*Number in inches is standoff distance
** Based on jackhammer efficiency = 65%
flame jet efficiency at 14in. = 2%
at 10in. = 3%
at 6 in. = 7%

TS_ _ = Table speed rheostat setting
B _ = Drill bit used

NK = No kerf
KA = Kerf A
KB = Kerf B
NO = No offset
Off1 = 1in. offset
Off2 = 2in. offset
S = Simultaneous
I = Independent

The constants used in these theories were based on the analysis of cylindrical samples of Missouri red granite, 2-1/4 in. diameter and 1/2 in. thick, weighing 81.95 grams that were crushed in drop weight tests (Table VI). Therefore it was necessary to divide the computed number by 81.95 and multiply by the weight of the analysis sample to obtain the correct surface breakage energy in ft-lb. This value was then multiplied by 2, 4, or 8 according to the number of times the chipping sample had been subdivided, to obtain the total surface breakage energy. The total surface breakage energy was divided by the total chipping sample weight to obtain the specific surface breakage energy in ft-lb/g, which was then converted to joules/cc.

The results from two drop weight tests at known energy inputs (drop heights) are plotted on semi-log cumulative particle size distribution paper (Figure 6). The particle size distributions from the chipping tests with and without thermal treatment were plotted on the same scale (Figures 7-12) and the results summarized numerically in Table V.

The available energy (Table V) was the energy calculated from Eq. (4-1) and stoichiometric calculations for the jackhammer and flame jet respectively, multiplied by the efficiency. This number was divided by the material removed, to obtain the specific available energy.

Gross and Zimmerly (22-23) have shown that particle size is a reasonably accurate measure of the surface area formed during a fragmentation process. Further, they have shown that the energy required for fragmentation (i.e. the energy required for the formation of surface area) is directly related to particle size in accordance with the Rittinger law of crushing. Felts, et al. (24) have employed the Rittinger, Kick, and Bond theories to determine the specific energy of breakage for

TABLE VI

Drop Weight Test Results

Test	Sample Weight (g)	Drop Height (m)	Breakage Energy (joules)	Rittinger Constant K_R	Kick Constant K_K	Bond Constant K_B
A	81.95	3.66	649.	0.038750	2.3541	0.58513
B	81.95	2.75	326.5	0.037133	1.4288	0.44522

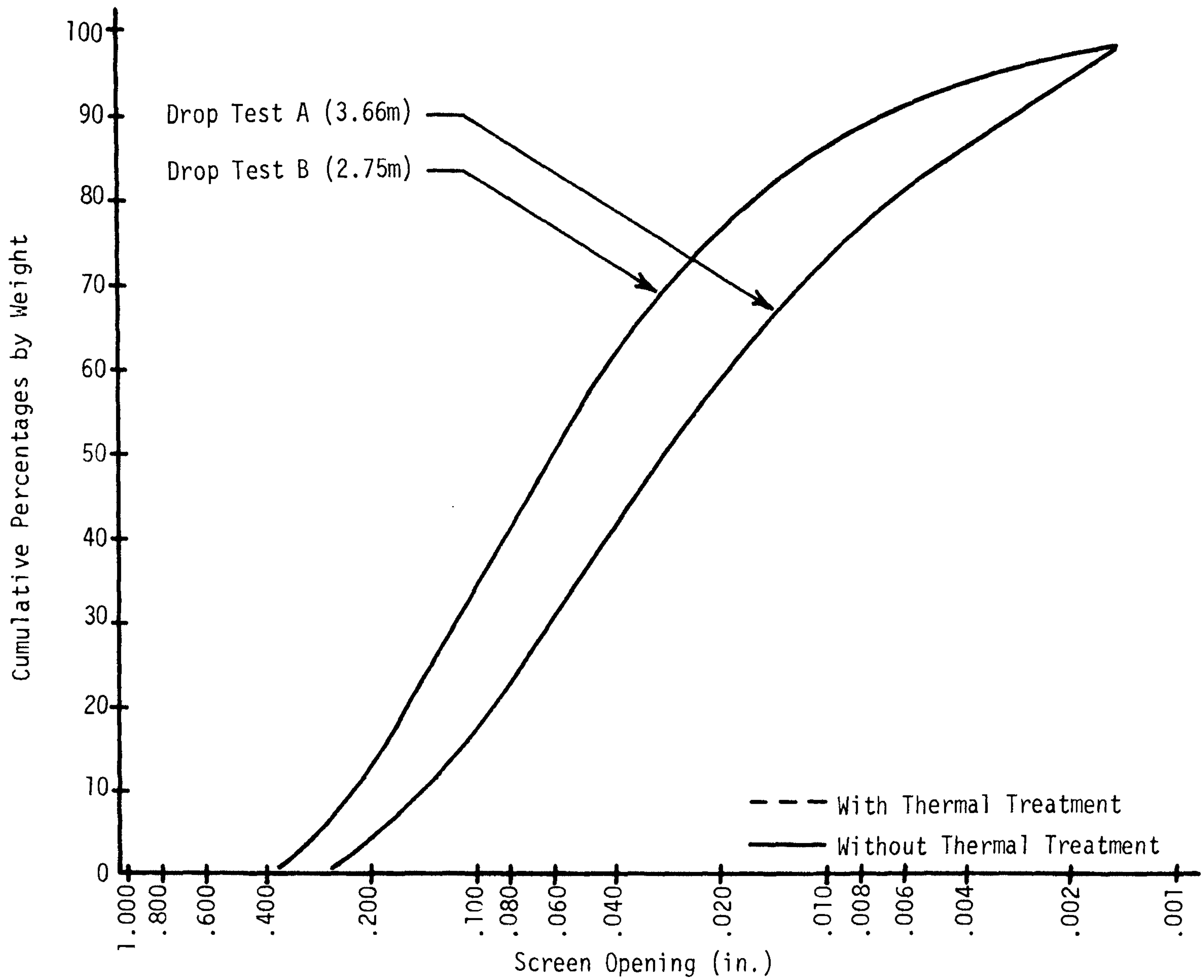

Figure 6. Particle Size Distribution for Drop Weight Tests

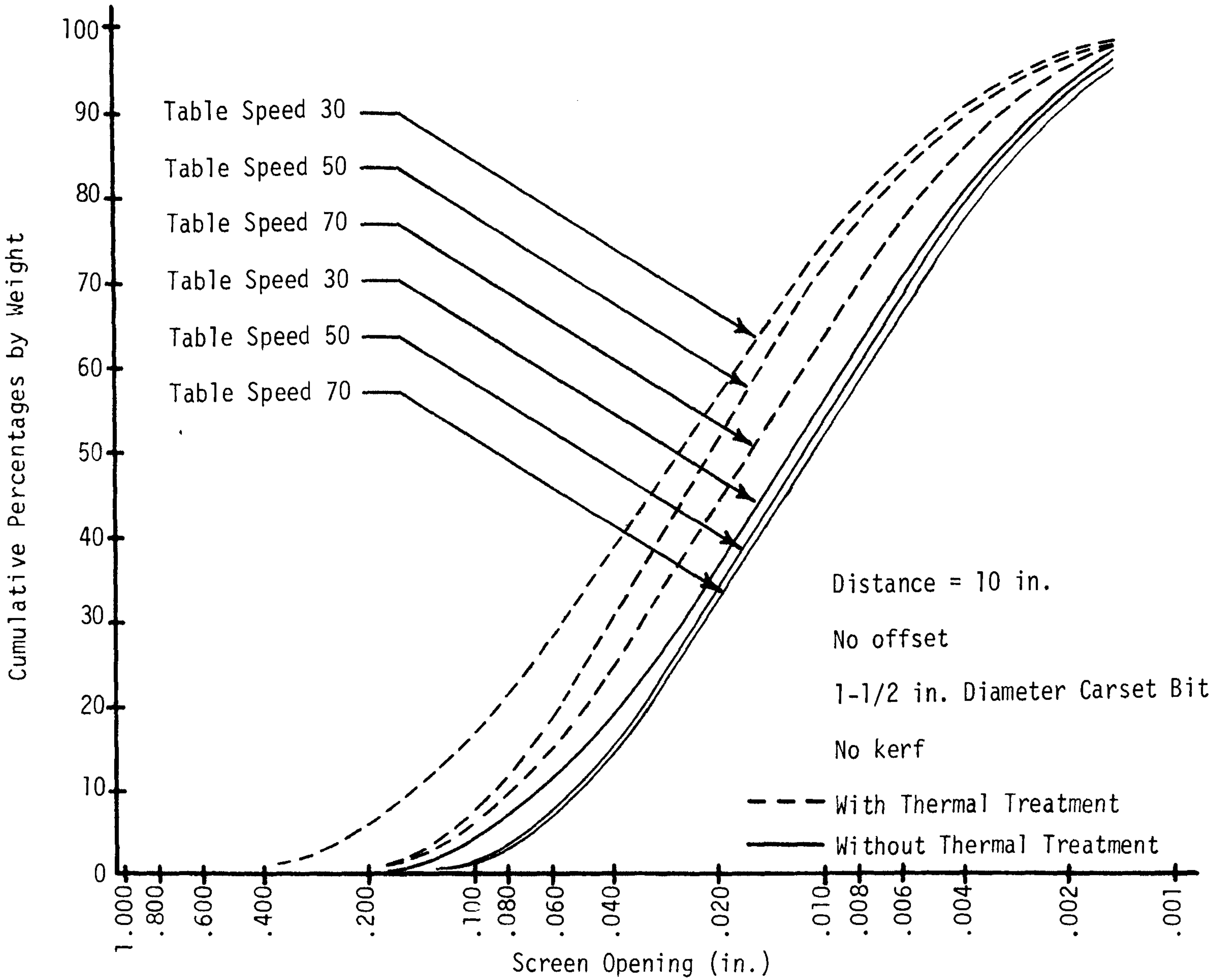

Figure 7. Particle Size Distribution Comparing Effect of Table Speeds

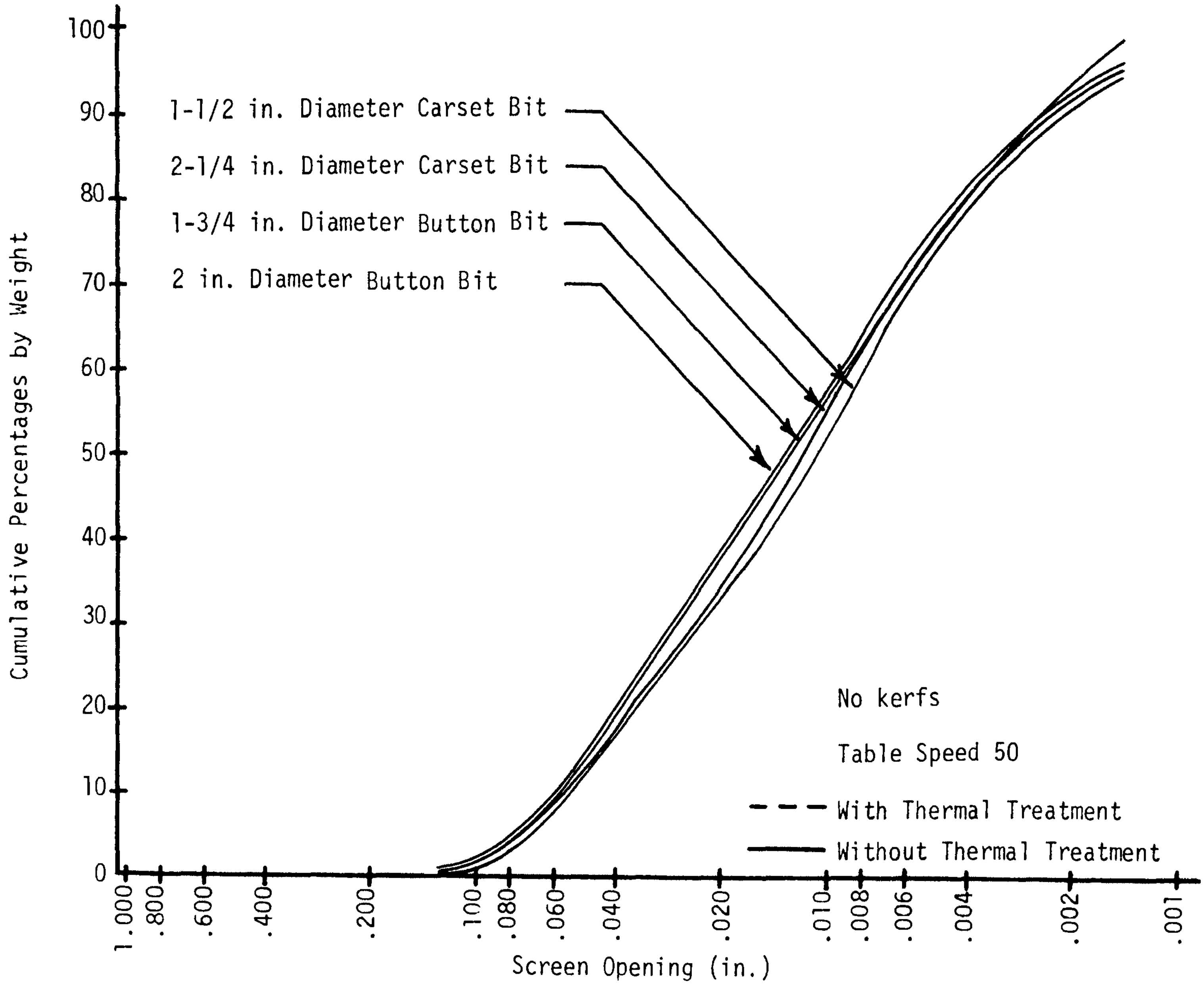

Figure 8. Particle Size Distribution Comparing Effect of Bit Size and Style

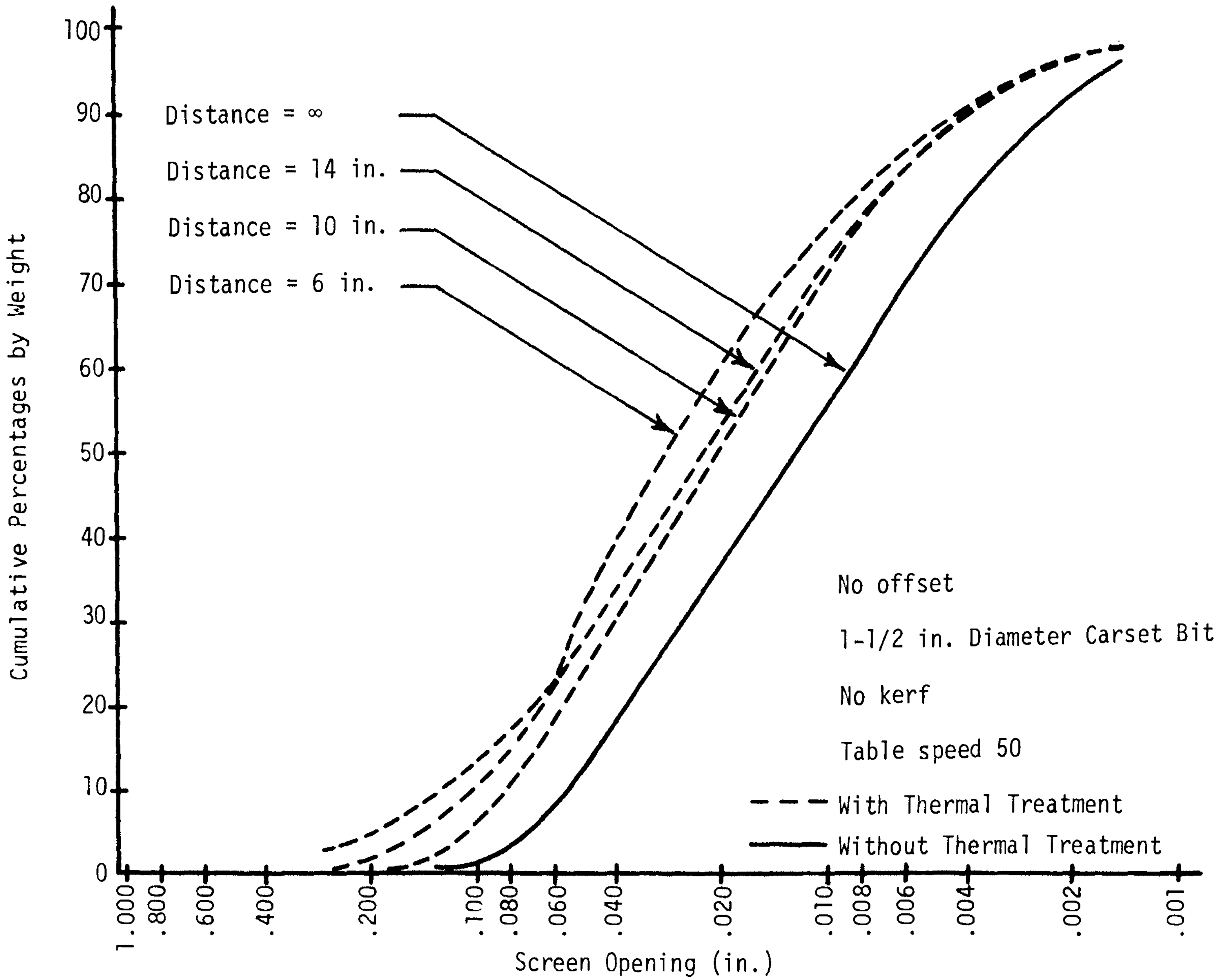

Figure 9. Particle Size Distribution Comparing Effect of Distance of Jet from Rock Face.

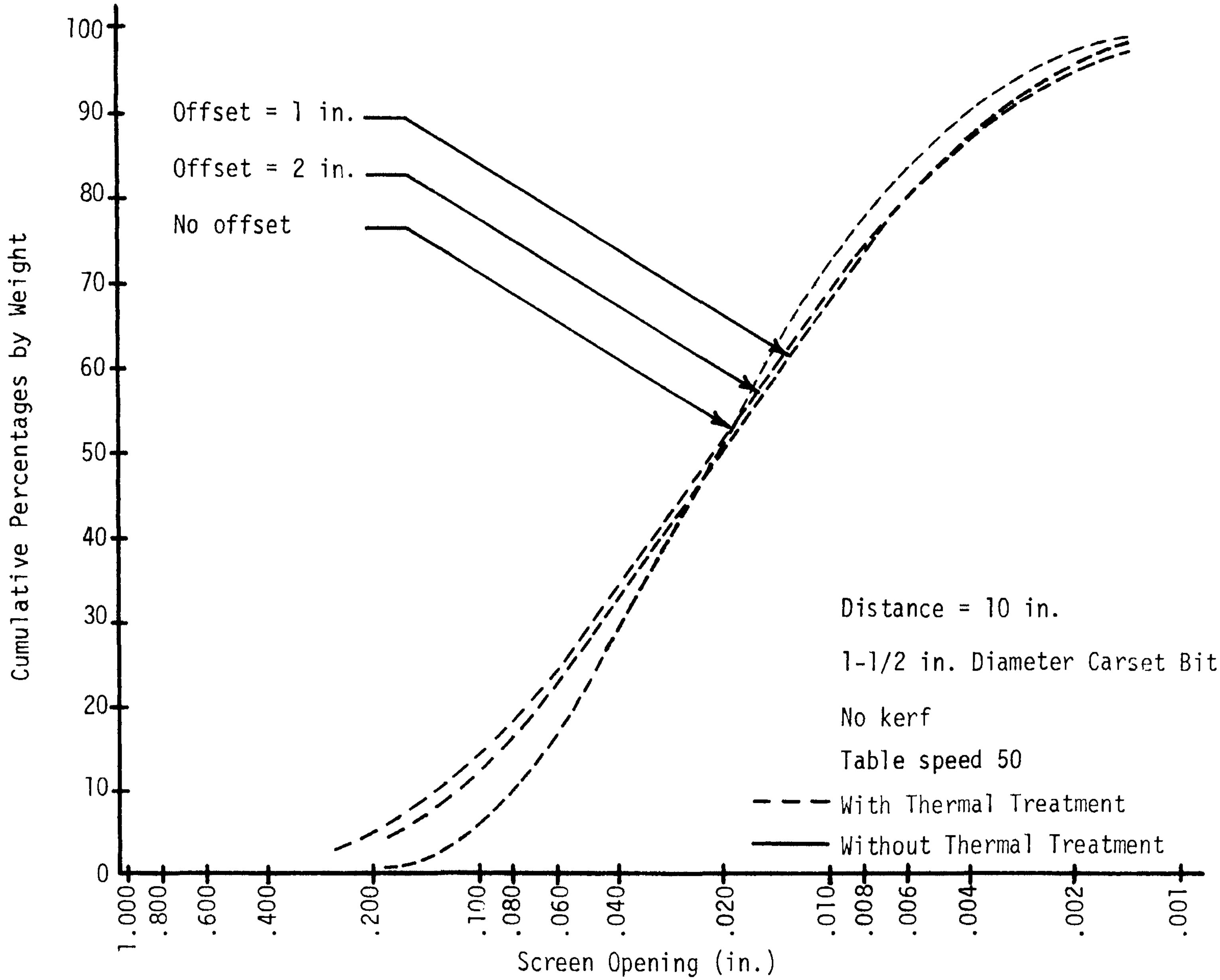

Figure 10. Particle Size Distribution Comparing Effect of Offset

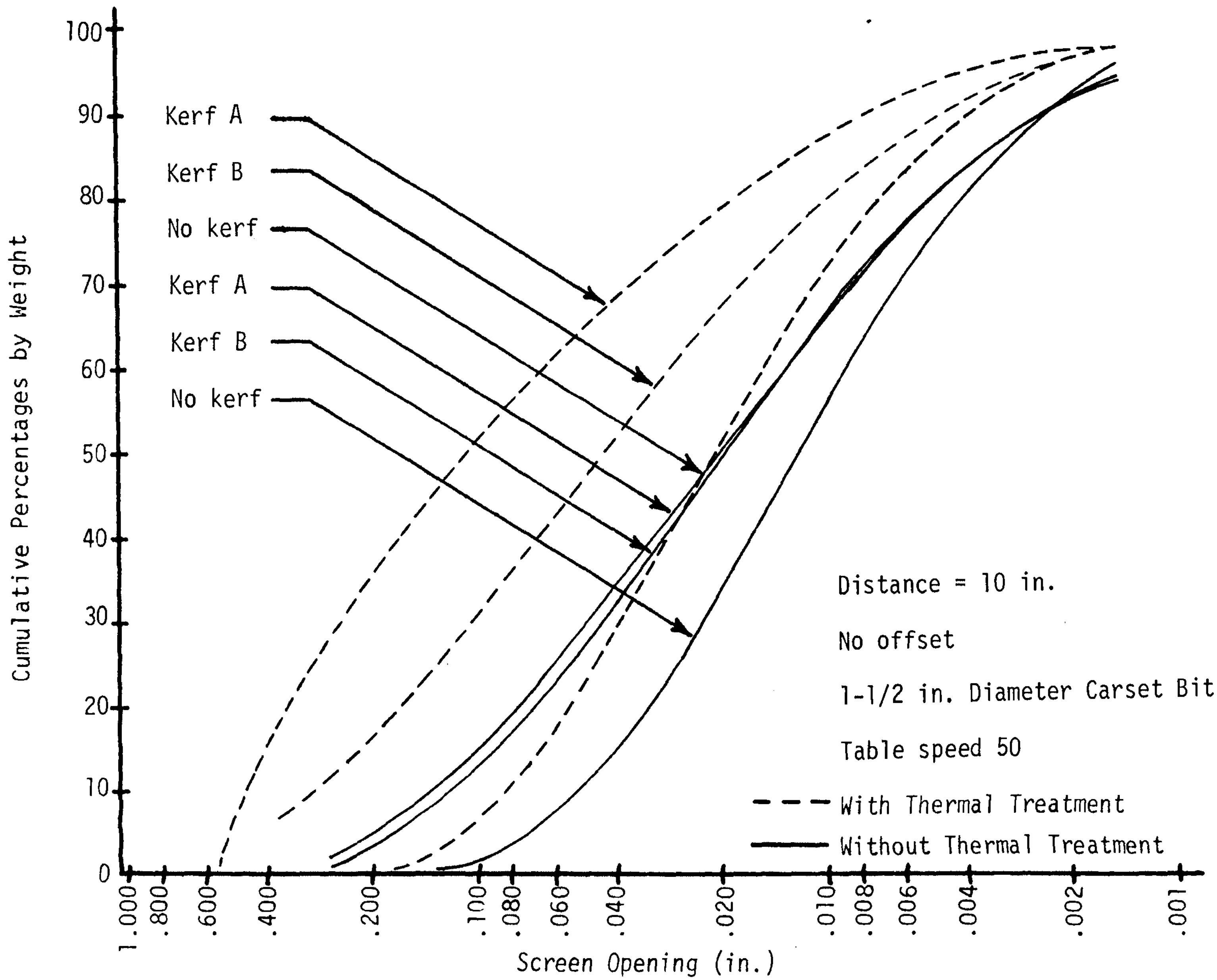

Figure 11. Particle Size Distribution Comparing Effect of Kerfs

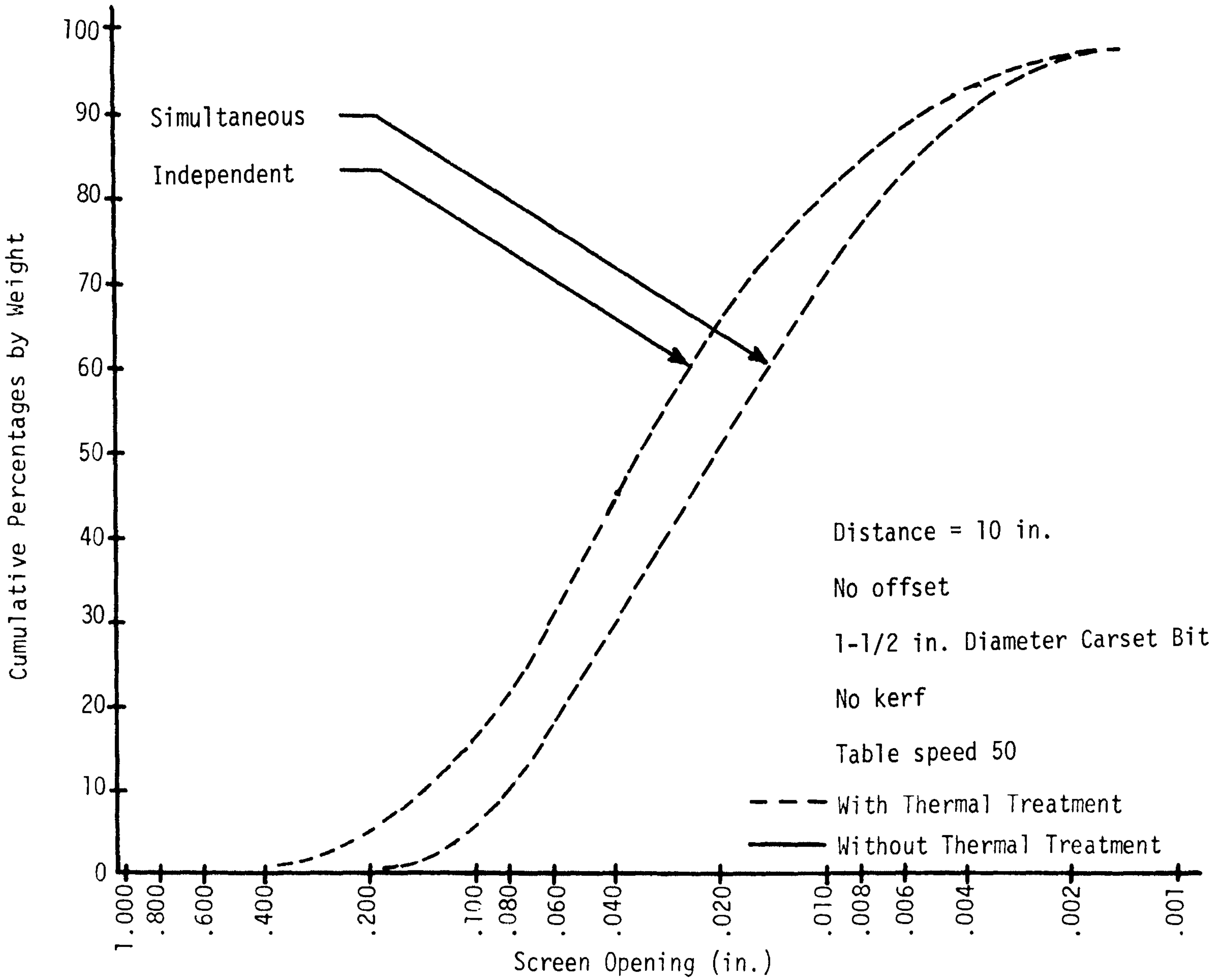

Figure 12. Particle Size Distribution Comparing Effect of Simultaneous and Independent Operation of Flame Jet and Jackhammer

explosives. Rittinger's, Kick's, and Bond's constants were calculated from results of drop weight tests (Table VI) in this investigation. Rittinger's theory was selected because it takes into account the fine particles generated by thermomechanical fragmentation and it gave a more consistent energy constant for different particle distributions. The Rittinger theory can be expressed mathematically as:

$$E_2 = K_r \left\{ \sum_{i=1}^{n} pct_i \frac{1}{d_i} - \frac{100}{d_o} \right\}$$

where:

E_2 = Surface area breakage energy (ft-lb)

d_o = Diameter of unbroken rock (in.)

d_i = Average diameter of screen fractions of rock particles (in.)

pct_i = Percent weight of diameter d_i

n = Number of screens

$\sum pct_i$ = 100 percent

The value of d_o that was used was 30 in., because that was the size of the rock from which the particles were chipped. The material removed from any given test would fit into a spherical shaped container with a 5 in. diameter. If a value of 5 in. instead of 30 in. were used for d_o, it would not change any observed trends in the results and would change the magnitude of the surface area breakage energy by no more than 0.2 percent.

A correction factor (25) was applied to the particle diameters before energy was calculated. The particles tended to be flat chips rather than cubic shapes. The correction factor was calculated from the following equation (Appendix C):

$$d_{cor} = \left(\frac{6}{4+2c}\right)d \tag{4-2}$$

where:

d_{cor} = Corrected diameter (in.)

d = Particle diameter from sieve analysis (in.)

c = $100/\delta$

δ = Thickness of particles in percent of observed diameters

VI. RESULTS AND CONCLUSIONS

The performance of the testing apparatus and the reliability of the testing procedure were examined by conducting a series of tests on Missouri red granite. The trends observed herein were based on the specific surface breakage energy calculated from these initial tests.

Results on the table speed factor without thermal treatment indicated that slower speeds were better than faster speeds. The specific surface breakage energy was 28.63 j/cc at table speed 30 compared to 32.08 j/cc at table speed 70. The application of thermal treatment reduced the specific surface breakage energy by as much as 41 percent, and the trend of slower table speeds being more effective was maintained.

Four different drill bits were tested without the application of thermal treatment. It was found that the larger diameter bits showed some improvement over the smaller diameter ones for both cross bits and button bits, and that the large bits were approximately the same in specific surface breakage energy for the two styles. However, the large button bit removed 365.4 grams of material, whereas the large cross bit removed only 237.1 grams, so that the large button bit was more efficient if compared on a basis of specific total energy.

When the heat source was 14 in. from the face of the rock there was a 62 percent reduction in specific surface breakage energy when compared to the case when no thermal treatment was used. At closer distances the process was even more improved (85.5 percent reduction in specific surface breakage energy at the 6 in. standoff distance). At the 6 in. standoff distance some spalling took place which accounts for part of the decrease in specific surface breakage energy.

Contrary to data presented by Carstens et al. (12) for heat treatment by laser, it was found that with flame jet thermal treatment, offsetting the cutter from the path of heat treatment increases the specific surface breakage energy and lessens the amount of material removed.

The use of kerfs increased the material removed and decreased the specific surface breakage energy. When no thermal treatment was applied, the specific surface breakage energy was lower for Kerf B (25.53 j/cc) than it was for Kerf A (26.44 j/cc). When thermal treatment was applied the reverse was true (Kerf A, 8.99 j/cc; Kerf B, 13.15 j/cc). This means that thermomechanical fragmentation works better on narrower, deeper kerfs such as Kerf A.

The high velocity exhaust from the flame jet blows away some rock particles, with smaller particles being more susceptible. A test was run in which the flame jet was operated independently from the jackhammer and then shut off during the chipping process. The test was not completely comparable because the rock cooled, and lost some thermal energy before the jackhammer was applied. The results were that approximately twice as much material was collected during independent operation, which indicated that many particles were blown away during simultaneous operation. The specific surface breakage energy was lower for the independent test, which indicated that it was indeed the smaller particles that were lost.

VII. RECOMMENDATIONS

This research produced a testing apparatus and process by which the effects of thermal treatment may be evaluated. The following is a list of recommendations for future research:

1.) Provide a closed system in which it can be assured that a minimum of particles are lost because of flame jet exhaust.

2.) Test other types of hard rocks that have both lesser and greater degrees of spallability.

3.) Conduct tests with thermal energy sources other than the flame jet, such as infrared heaters.

4.) Conduct tests with other types of mechanical cutters. A preferable mechanical cutter would be one designed to remove surface rock rather than drill a conventional hole.

5.) Use a statistical analysis or an averaging process based on three or more tests at the same operating conditions.

Currently a number of these recommendations are under consideration in research being carried out by the University of Missouri-Rolla, Rock Mechanics and Explosives Research Center.

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IX. VITA

Gary Earl Fenton was born on September 13, 1947, in Sedalia, Missouri. He received his primary and secondary education in Tipton, Missouri. He received a Bachelor of Science Degree from the Department of Mechanical Engineering at University of Missouri-Rolla, in January, 1970.

Since then he has been enrolled in the Graduate School of the University of Missouri-Rolla and associated with the Rock Mechanics and Explosives Research Center-U.M.R. as a graduate research assistant.

APPENDIX A

GAGES AND EQUIPMENT

1. OXYGEN FLOWMETER

A Fisher and Porter No. 10A1735A flowrater with horizontal screwed connections and brass end fittings based on a specific gravity of 1.10 and a flow rate of 8.33 CFM oxygen, was used to monitor the flow of oxygen.

2. FUEL FLOWMETER

A Matheson No. 700PSV, 250 mm panel mount flowmeter with standard needle valve based on a specific gravity of 0.819 and a flow rate of 0.0556 GPM (3-1/3 GPH kerosene), was used to control the flow of kerosene.

3. DRIVE MECHANISM FOR ROCK TABLE

A Boston Gear variable speed drive system was employed to move the rock table. A 3/4 horsepower, single phase, D.C. motor in conjunction with a constant torque reducer assembly moved the rock table laterally in front of the fragmentation equipment.

APPENDIX B

THE JACKHAMMER WORK OUTPUT EQUATION

1. DERIVATION (from Ref. 3)

Factor	Equation	Dimensions	
Force on working face of piston	$F = PA$	(lb)	(B-1)
Work on power stroke	$e = \frac{PAS}{12}$	(ft-lb)	(B-2)
Acceleration of piston on power stroke	$a = \frac{PAg}{W}$	(ft/sec^2)	(B-3)
Time of power stroke	from $S = 1/2\ at^2$ $t = \left(\frac{WS}{6PAg}\right)^{\frac{1}{2}}$	(sec)	(B-4)
Time of piston round trip	$T = (1+K)\left(\frac{WS}{6PAg}\right)^{\frac{1}{2}}$	(sec/blow)	(B-5)
Blow per minute	$n = \frac{60}{1+K}\left(\frac{6PAg}{WS}\right)^{\frac{1}{2}}$	(blow/min)	(B-6)
Total work output per minute	$E_1 = \left(\frac{\text{Work}}{\text{Blow}}\right)\left(\frac{\text{Blows}}{\text{minute}}\right)$		

$$E_1 = \frac{(60)\ 6^{\frac{1}{2}}\ g^{\frac{1}{2}}}{12(1+K)}\ \frac{P^{3/2}\ A^{3/2}\ S^{1/2}}{W^{\frac{1}{2}}}$$

(ft-lb/min) (B-7)

2. APPLICATION

To find the constant "C", it is necessary to determine the value of K (fraction of time of piston power stroke required for return stroke) since:

$$C = \frac{(60)\ 6^{\frac{1}{2}}\ g^{\frac{1}{2}}}{12(1 + K)} \tag{B-8}$$

Using Eq. B-5 and the cycles per second as given in Table II, the value of K is .828, and C equals 38.15 for the jackhammer used in this experiment.

APPENDIX C

THE PARTICLE SHAPE CORRECTION FACTOR

1. DERIVATION (25)

The theories that relate energy to surface area assume that the particles are spherical or cubic in shape. Since some of the particles collected from the thermomechanical fragmentation tests were flat chips, it was necessary to apply a particle shape correction factor.

Assuming that all particles were cubes having side d gives a surface area of $6d^2$. If the cube is split in half, the surface becomes $6d^2 + 2d^2$. For each additional split $2d^2$ surface area is created. Thus, cutting the cube by a number of parallel planes results in an increased surface area equal to twice the number of resulting parallelopipeds less one times the square of the diameter. Expressing the average thickness of the particles as a percentage of the observed diameter will give the new surface area as:

$$\text{surface} = 6d^2 + 2\left(\frac{100}{\delta} - 1\right)d^2 \tag{C-1}$$

where

d = observed diameter

δ = thickness of particles in percent of observed diameter

Letting $c = \frac{100}{\delta}$ the equation becomes:

$$\text{surface} = d^2(4 + 2c) \tag{C-2}$$

For the divided cube, the specific surface (surface per unit weight) becomes:

$$S_W = \frac{S_n}{\text{weight}} = \frac{(4 + 2c)d^2}{d^3\rho} = \frac{(4 + 2c)}{d\rho} \tag{C-3}$$

where

S_W = specific surface

S_n = surface of divided cube

ρ = density

From statistics, the corrected diameter (harmonic mean diameter) is expressed by:

$$d_{cor} = \frac{6}{\rho S_W} \qquad \text{(C-4)}$$

where

d_{cor} = corrected diameter.

Substituting for S_W gives:

$$d_{cor} = \frac{6}{\rho S_W} = \frac{6}{\rho \frac{(4 + 2c)}{d\rho}} = \frac{6}{4+2c} \quad d \qquad \text{(C-5)}$$

2. APPLICATION

Values of δ were calculated by measuring the thickness of a given particle, dividing that by the observed diameter of that particle and multiplying by 100. δ was calculated for numerous particles on any given screen. These numbers were averaged to yield a value of $\delta = 18.6$, hence $c = 5.38$. When substituted in Eq. C-5 this yields:

$$d_{cor} = .406 \ d \qquad \text{(C-6)}$$

This factor equates the flat particles to smaller diameter ones of the theoretically assumed shape with equivalent surface area. Particles with observed diameters of .065 or less were approximately cubic or spherical in shape, thus the correction factor was not applied to particles of that size or smaller.